US Department of Energy
Cooperative Agreement Number:
DE FC36-01CH11079

ADVANCED RECIPROCATING ENGINE SYSTEMS

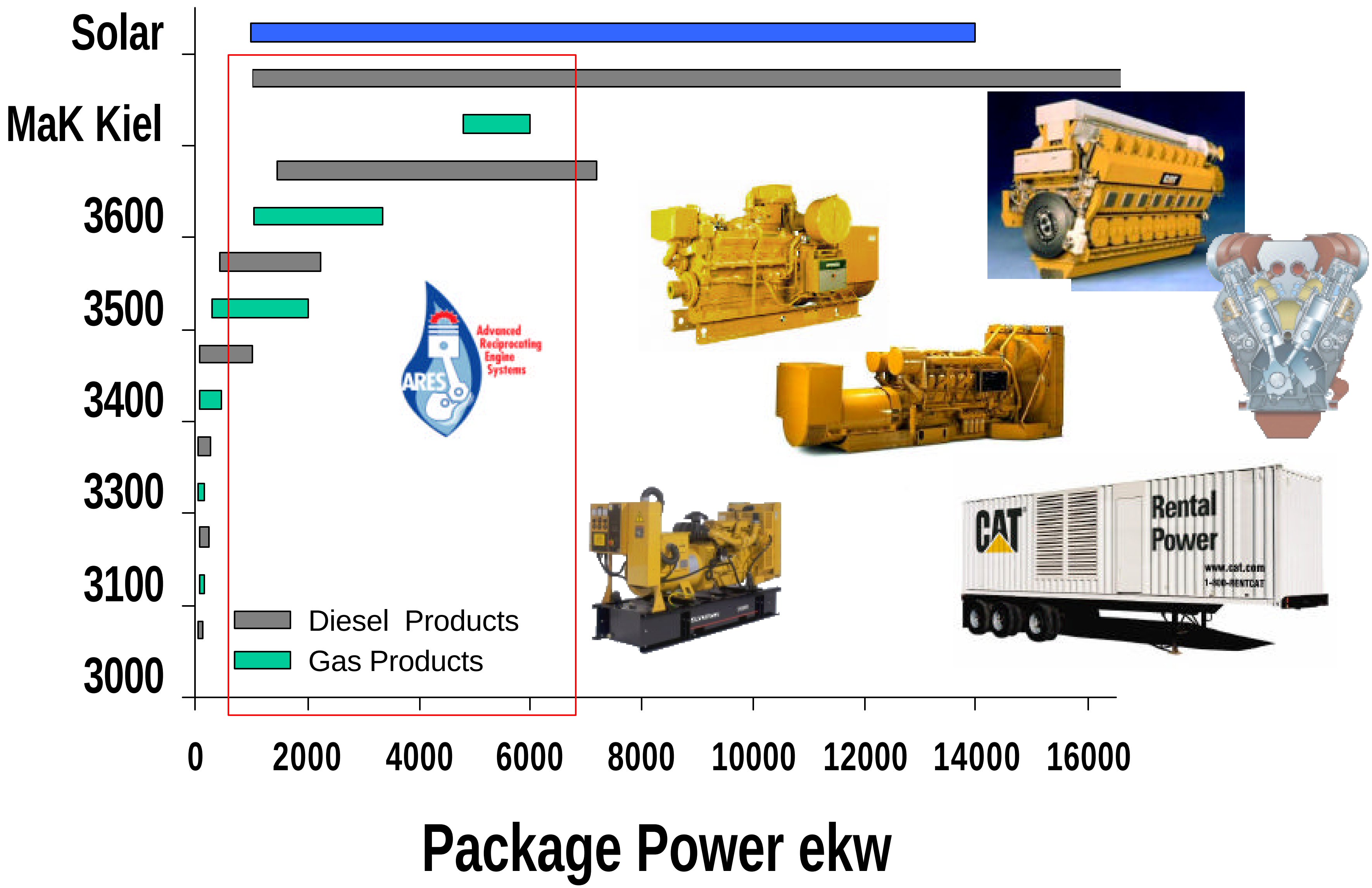
PEER Review December 2, 2003

Mr. Gordon Gerber Principal Investigator
Dr. Scott Fiveland Research Engineering Specialist

Agenda:

- Caterpillar Power Products
- ARES Program Overview at Caterpillar
- ARES Team Approach
- Program Phases and Key Results
- Research Program Review
- Milestone Update
- Program Risks / Opportunities
- Program Impact on Distributed Energy
- Summary and Near Term Plan

Caterpillar Power Products



ARES Program Overview at Caterpillar

Objective:

By 2010, create a natural gas powered reciprocating engine system with the following attributes:

- 50% thermal efficiency
- 0.1 gram/bhp-hr NOx or less
- 10% reduction in first cost / ekw
- No loss of reliability or availability

5 Key Development Areas

Approach:

Phased Introduction

I 44% Efficiency
0.50 g/bhp-hr NOx
2004 Intro

II 47% Efficiency
0.1 g/bhp-hr NOx
2007 Intro

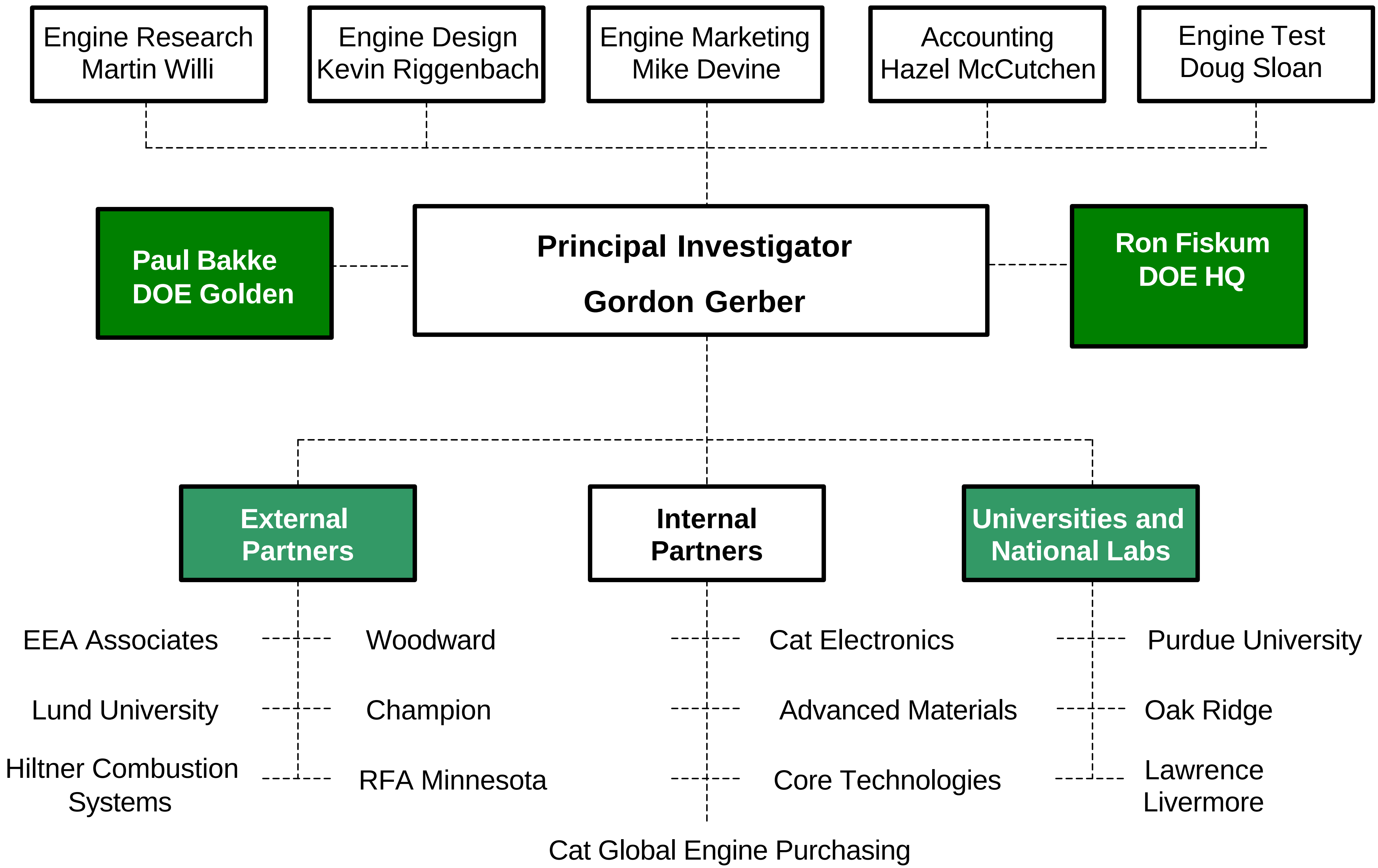
III 50% Efficiency
0.1g/bhp-hr NOx
2010 Intro

Program Budget

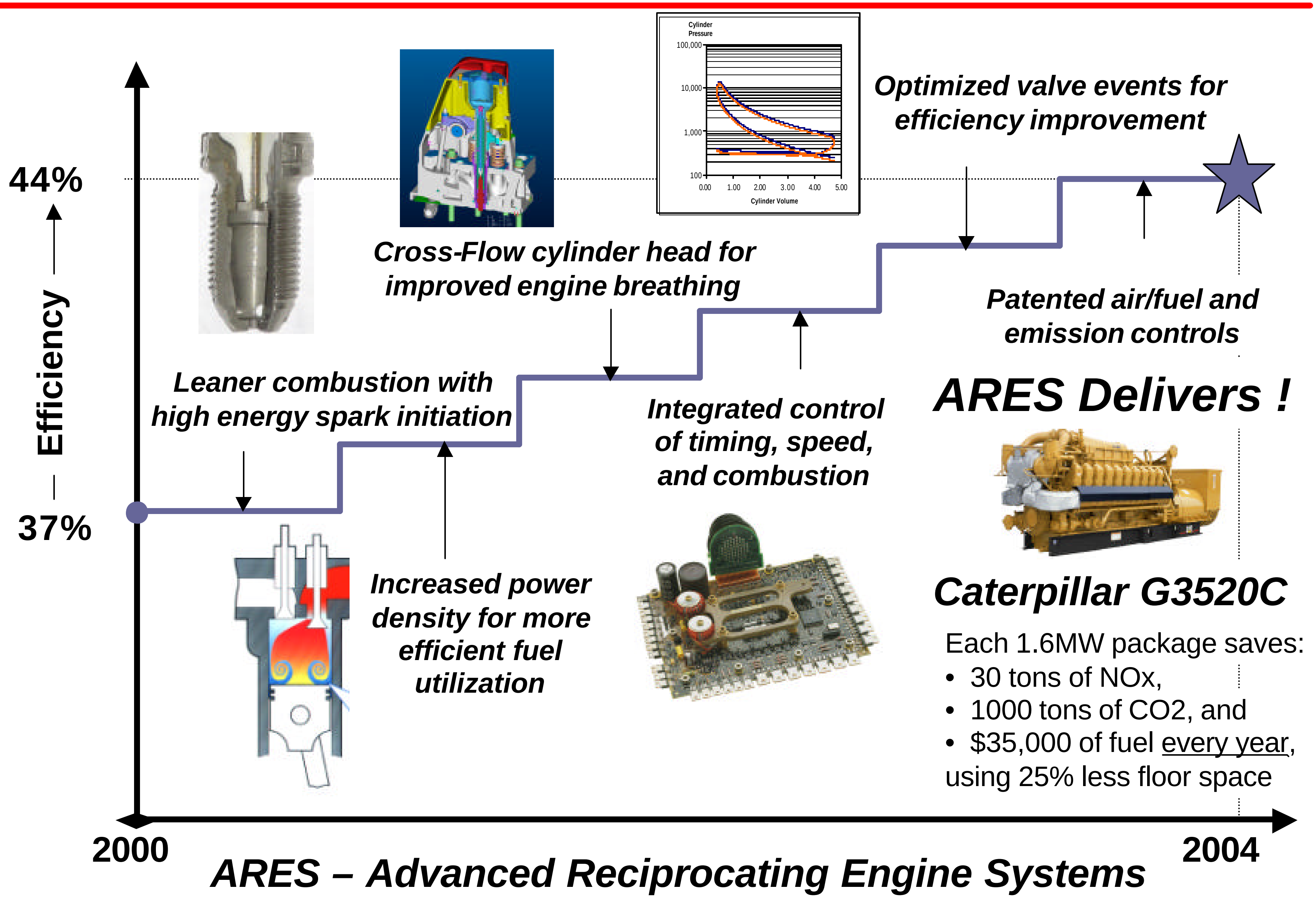
Required $70M+
Allocated $20.5M

Task Description		Phase I	Phase II	Phase III
Task 1	Component Development / Test	Complete	Underway	Underway
Task 2	Systems Development / Test	Complete	Underway	
Task 3	Engine Integration / Prep	Complete		
Task 4	Engine Build / Lab Test	Underway		
Task 5	Pre-Commercial Demonstration	Underway		

ARES Team Approach

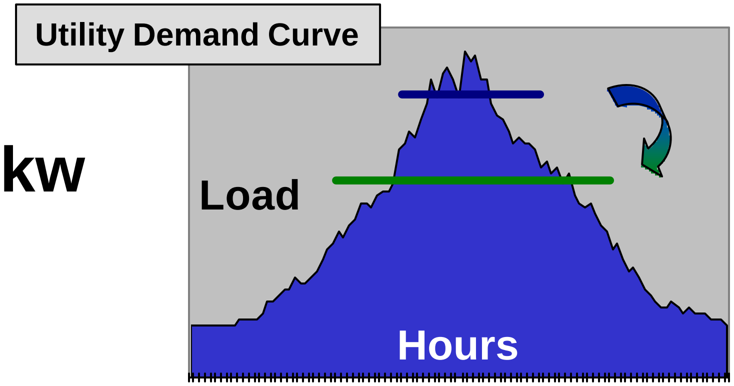


Phase I Approach



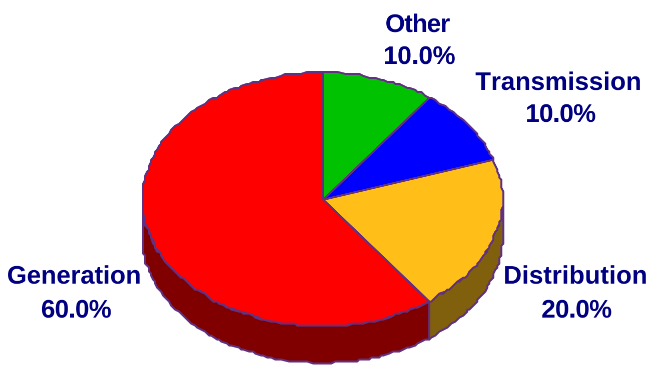
Marketplace Demands for ARES

1) **Attractive Life Cycle Cost**
   - Low Installed First Cost/ekw
   - Short Installation Cycle
2) **Power Quality**
3) **Reliability / Serviceability**



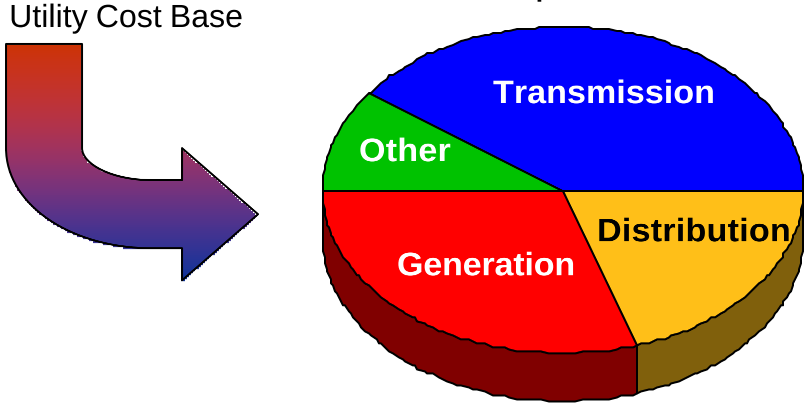
Improved Operating Cost/kw-hr
Allow Increased Time Online
100 – 500 hrs/yr ➡ 100 – 3000 hrs/yr

Keep local rates low, support local economy



Historical Utility Cost Base

Expected



Heber City Utah - DER at a Municipal Facility

Qty	Unit	Fuel	Output MW Each	Dispatched Cost/MW-hr	NOx G/bhp-hr
3	G3520C	Gas	1.85	$37-60	1.0
2	G3516C	Gas	1.50	$37-60	1.0
2	G3516B	Gas	0.75	$39-72	1.0
1	G399	Gas	0.65	$42-78	1.2 w/ SCR
2	3516	Diesel	1.5	$80-122	.06 w/ SCR

3 x G3520C Units Commissioned 4th Quarter 2002

- 9000 Hours of Operation to Date
- 3000 hrs / year, hourly start / stop cycles
- 5600 feet altitude at 92% power capability
- Full rated power between –20F and 110F

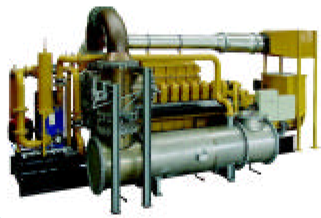
99%+ Availability to date

All Operating Cost Targets Met

Fuel Prices:
Gas at $2.00 to $5.00/mm Btu
Diesel at $0.75 to $1.25 / Gallon

Marketplace “Pull” for ARES Technology

204 MW of ARES Power Installed or in Process



G3520C CHP

North America
47 MW
DER / Power Security
Power Quality

Europe / Africa / Mid-East
34 MW
CHP / Prime Power

Asia / Australia
97 MW
CHP / Prime Power

Central and South America
26 MW
Prime Power

1500 MW Total Projects Quoted, Apr - Nov 2003
- Projects sizes between 1.6MW and 300MW
~ 75% of In-Process Volume is Export!

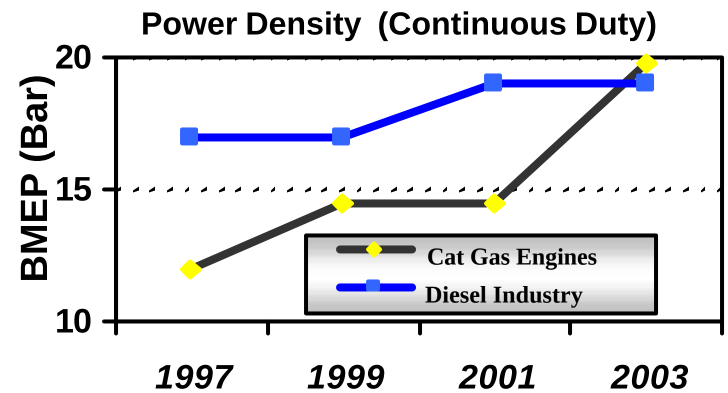
ARES Delivers!

CAT® Electric Power

Phase I ARES Successes

- **Power Density Impact**

  Phase I ARES Gas Engines have higher power density than comparable Diesel Engines at continuous ratings



- **Efficiency Impact**

  Phase I Gas engines are 7 points, or 19%, more efficient than pre-ARES models.

- **Emissions Impact**

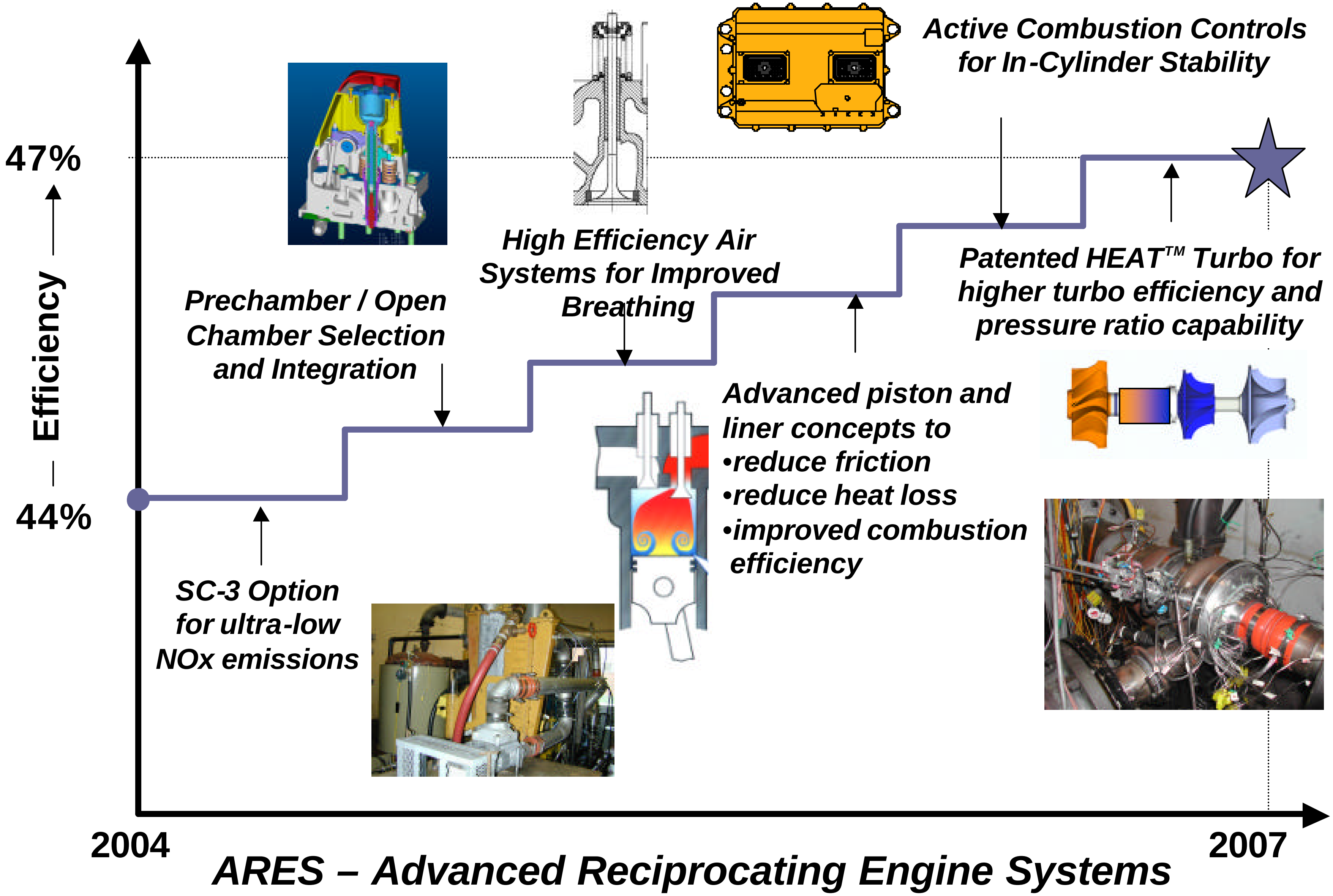
  Phase I Gas engines are 75% cleaner on NOx than pre- ARES models.

ARES Delivers !

- **Market Impact**

  Early Phase I Gas engines are now being commercialized in worldwide applications.

Phase II Building Blocks

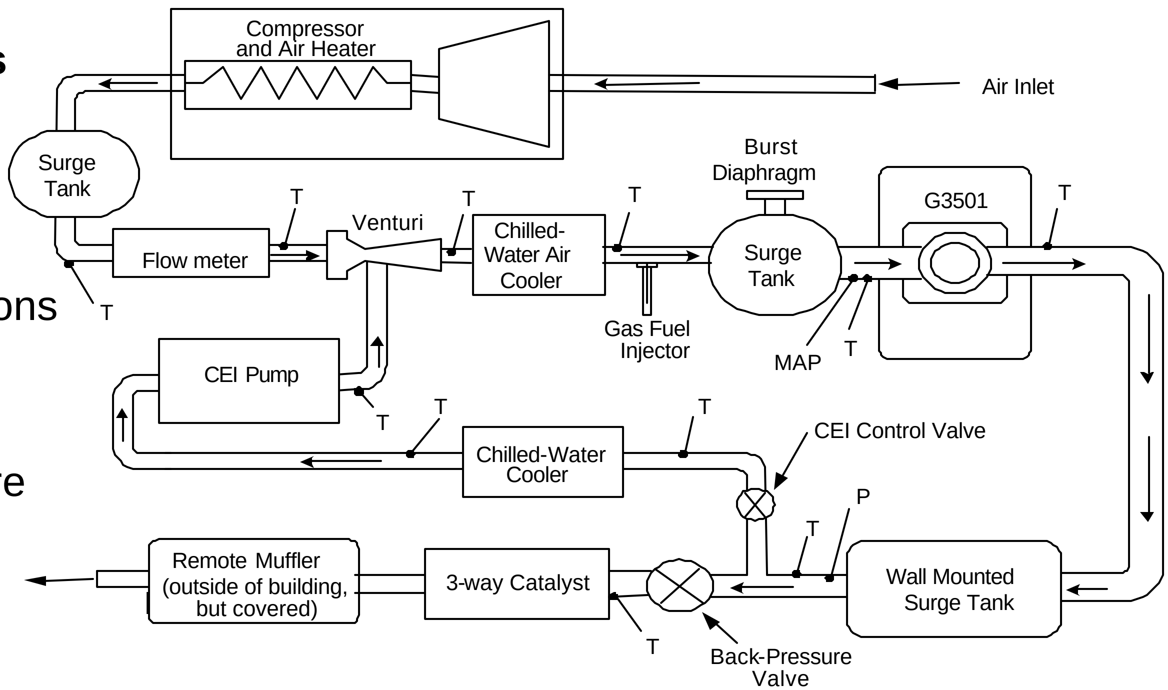


SC-3 Development Option

<u>**S**</u>toichiometric - <u>**C**</u>lean Exhaust Induction – <u>**3**</u> Way Catalyst

Cat 3501 Engine SC-3 Test Goals

- Map of engine performance
  - Engine efficiency
  - Window of operation
  - Extreme operating conditions
- Achieve catalyst out NOx emissions < 0.1 g/bhp-hr
- Determine if structural limits are reached
- Determine peak SC-3 BMEP



		2003					2004											
Item	Task	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Define Team and Project Scope																	
2	Concept Selection																	
3	Write System Level Specifications																	
4	Mechanical Design and Analysis																	
5	Control System Design and Analysis																	
6	Procure Parts																	
7	Multi-Cylinder Build																	
8	Test and Development																	
9	Design and Software Updates																	
10	Lab Endurance																	

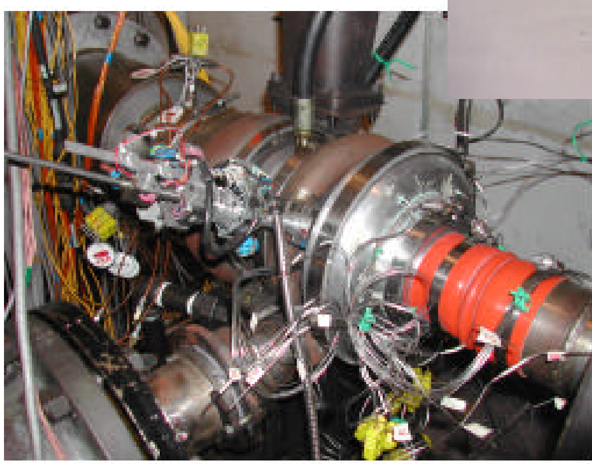
HEAT™

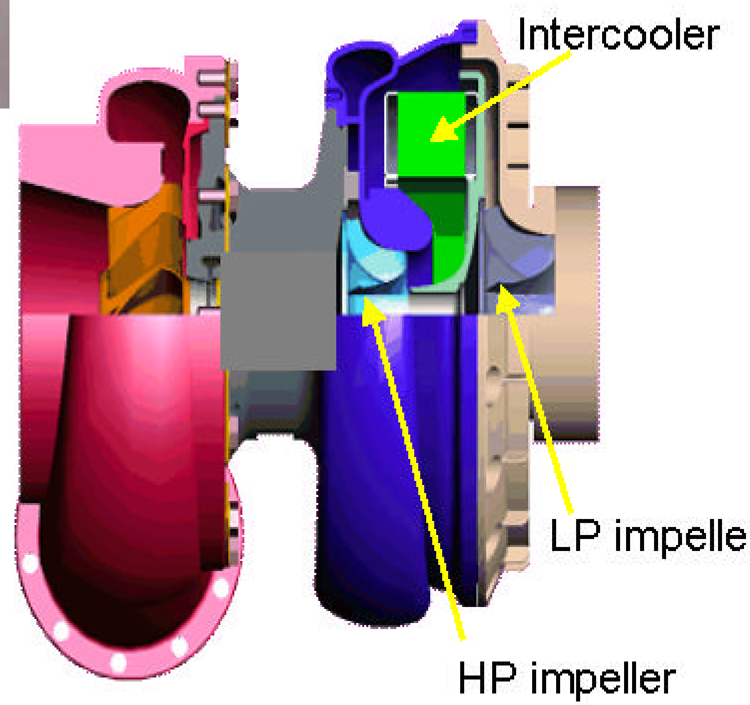
High Efficiency Advanced Turbocharging

Key Phase II Enabler

Pressure Ratios above 4.5
Efficiencies above 70%
2X Expected Bearing Life
Lower Package Costs

Gas Stand Tests Underway
Initial Tests Positive

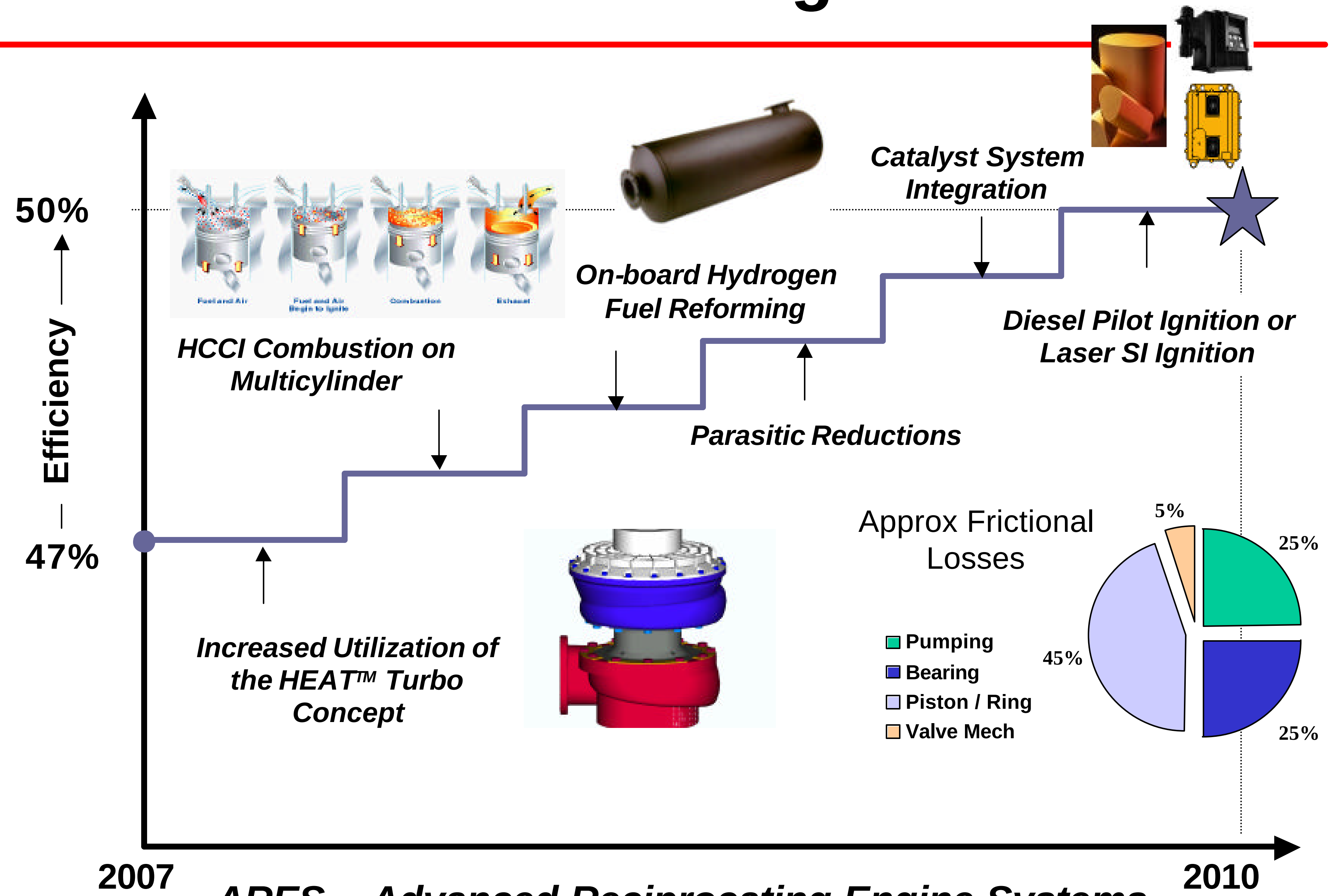




Titanium Aluminide Turbine Wheel Development

Cooperative CRADA Agreement with Oak Ridge Nat Labs

Phase III Building Blocks

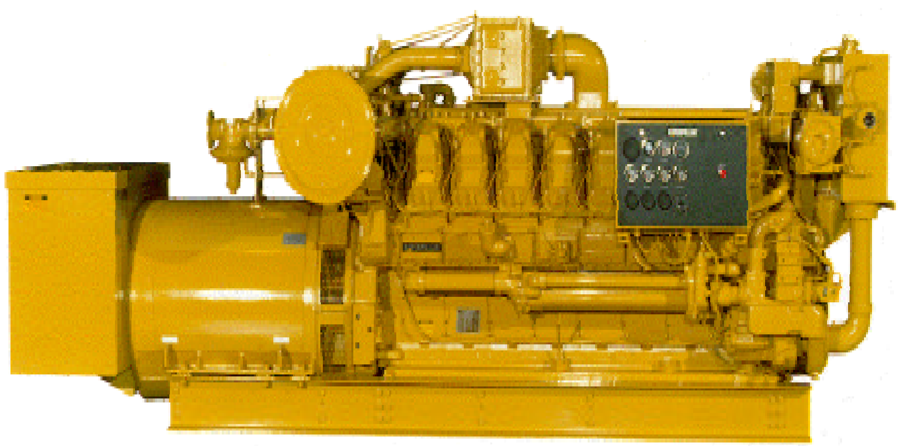


ARES – Advanced Reciprocating Engine Systems

Research Program Review

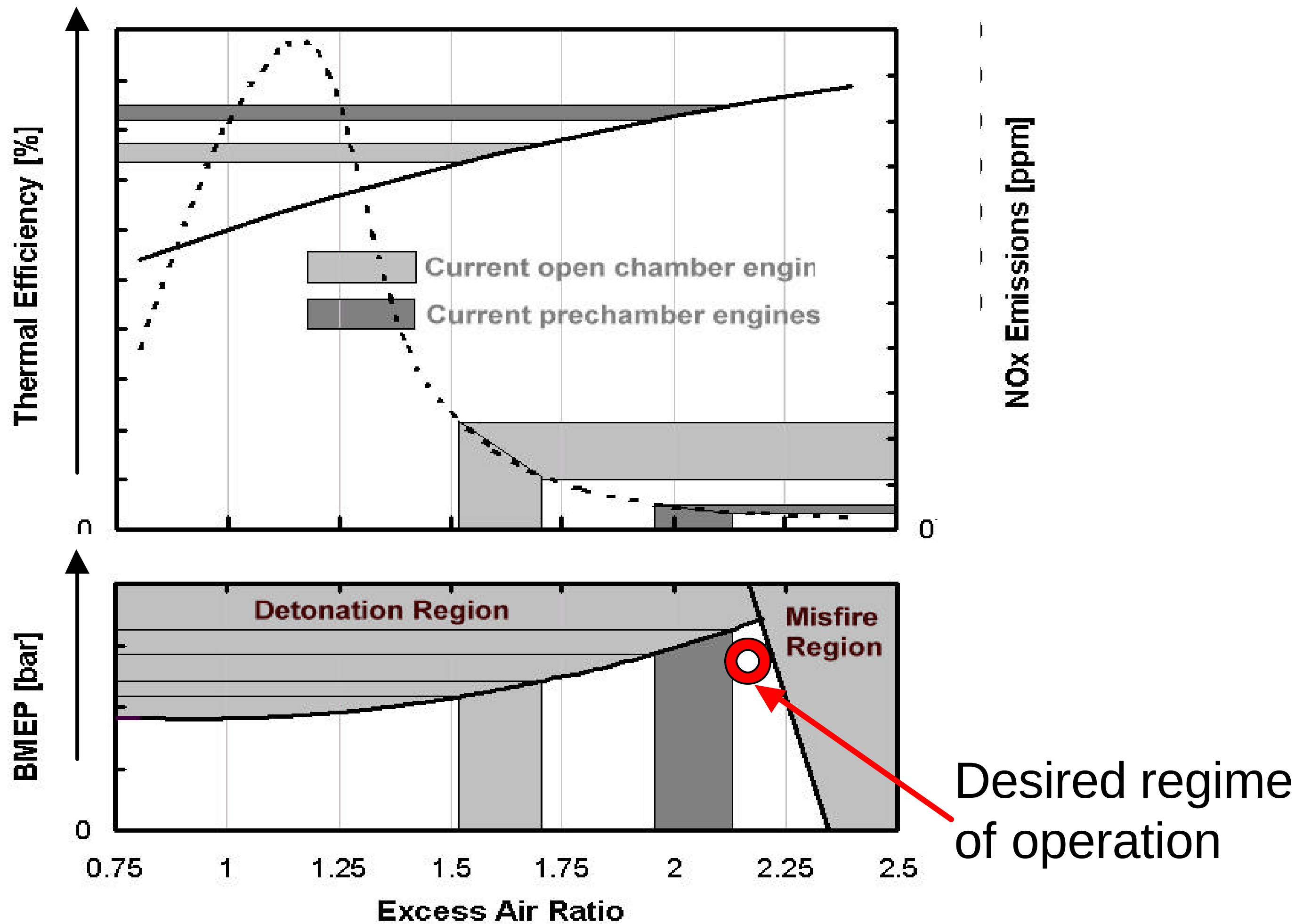
Dr. Scott Fiveland

- Performance Emissions Challenge
- Simulation Tools
- Phase II & Phase III
  - Reformed Fuels
  - HCCI
- Next Steps



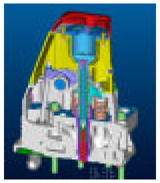
LEAN BURN COMBUSTION

Performance Characteristics



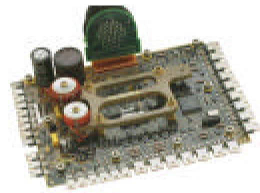
Advanced control strategies needed to evolve lean burn technology

ARES Technology Evaluations



Cross-Flow cylinder head

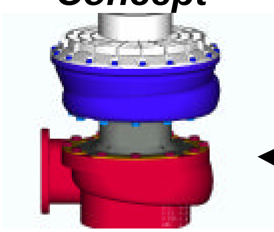
Integrated control of timing, speed, and combustion



Leaner combustion with high energy spark initiation

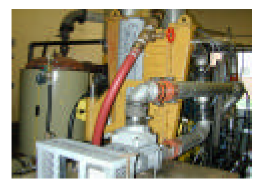
Phase I
- Advanced Spark-Ignition Technologies
- Improved engine systems

Increased Utilization of the HEAT™ Turbo Concept



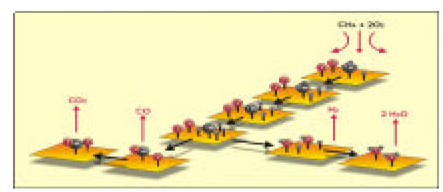
Phase II
- SC-3 Technology
- HEAT Turbo

SC-3 Option for ultra-low NOx emissions



HCCI Combustion on Multicylinder

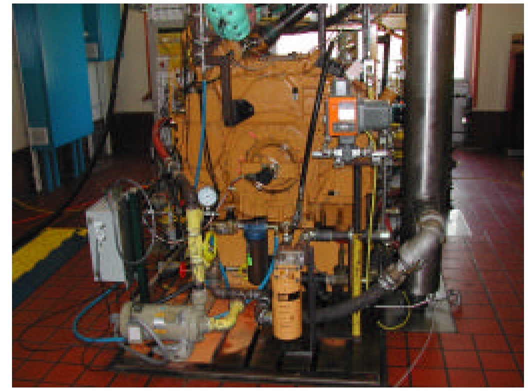
Phase III
- Reformed Fuel Technology
- HCCI
- Advanced SI technology w/ heat recovery



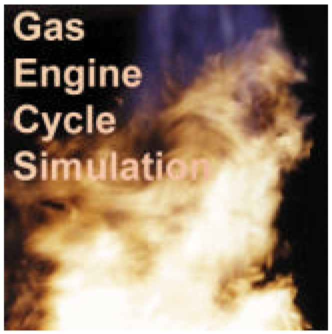
Catalyst System Integration

Caterpillar ARES Technology Evaluation

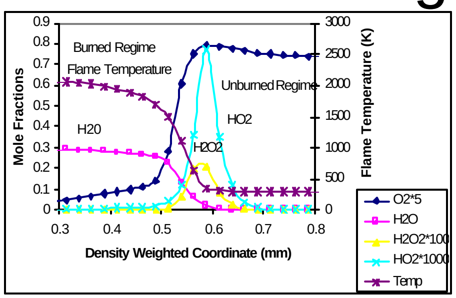
3501 Experiment

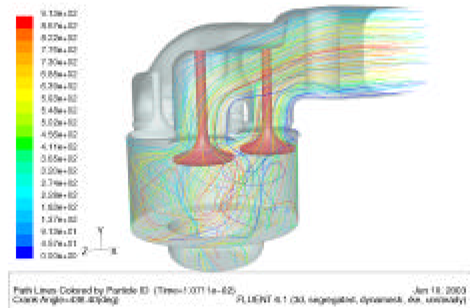


Analysis



Flame Modeling

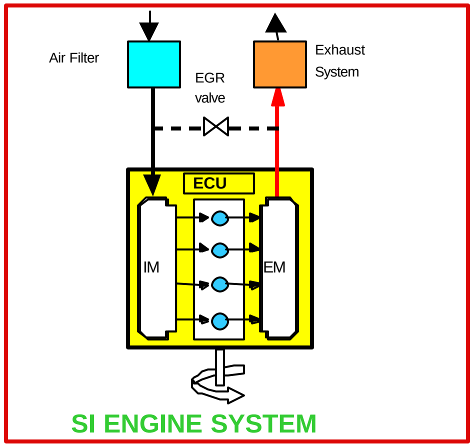


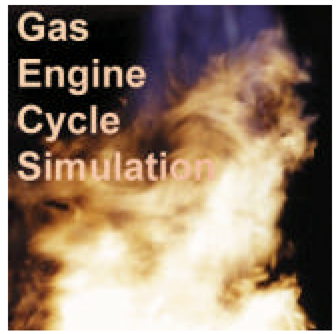


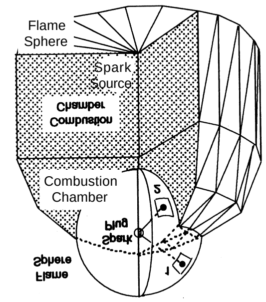
Detonation Modeling

GECS* Engine Simulation Model

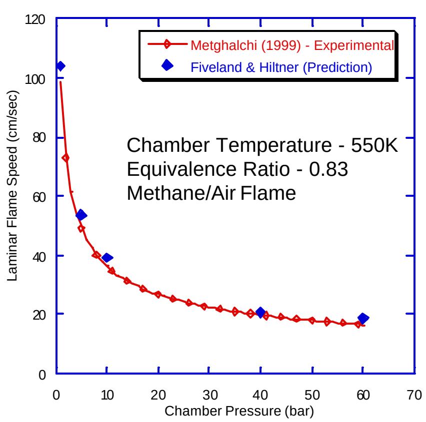
High Reynolds Number Flows







SwRI



$RH ? O_2 ? R ? HO_2$

$R ? O_2 ? olefin ? HO_2$

$R ? O_2 ? RO_2$

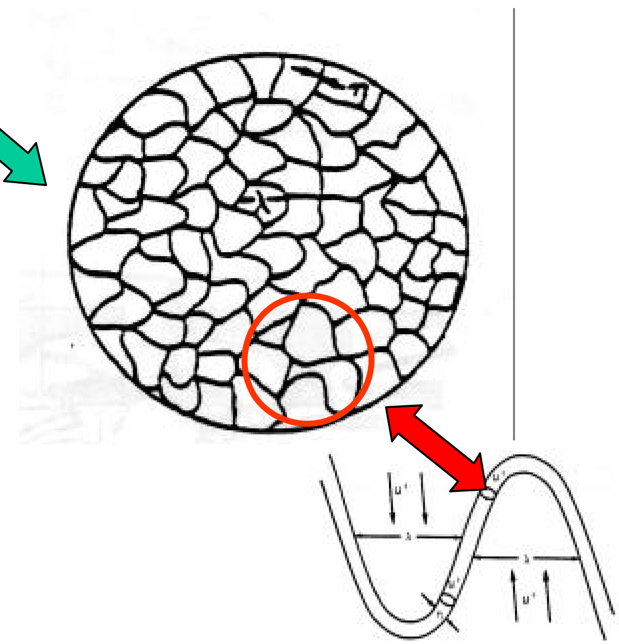
$RO_2 ? RH ? ROOH ? R$

$RO_2 ? R'CHO ? R''O$

$ROOH ? RO ? OH$

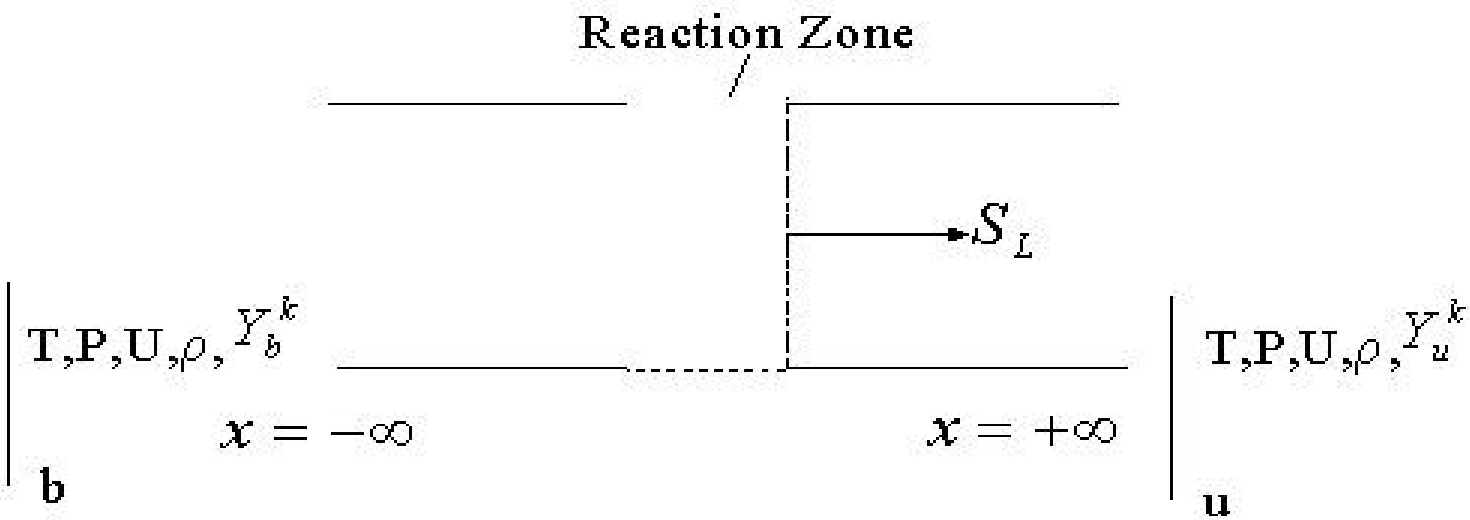
$RO_2 ? destruction$

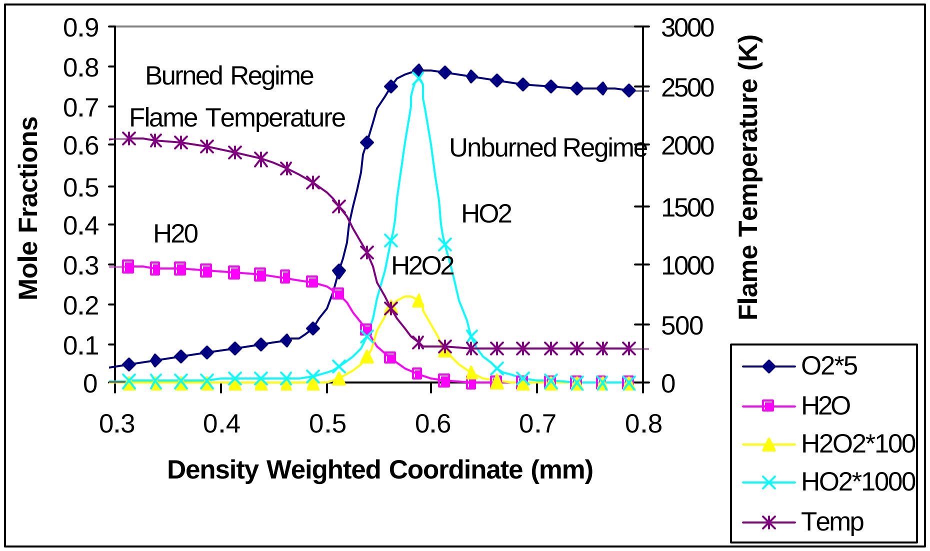
$R'CHO ? O_2 ? R'CO ? HO_2$

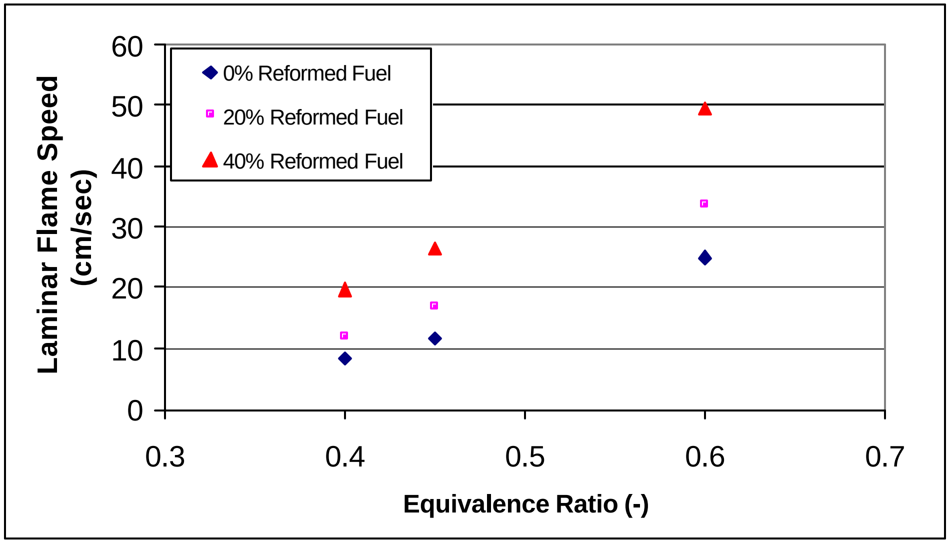


* Gas Engine Cycle Simulation

CFLAME* Result:

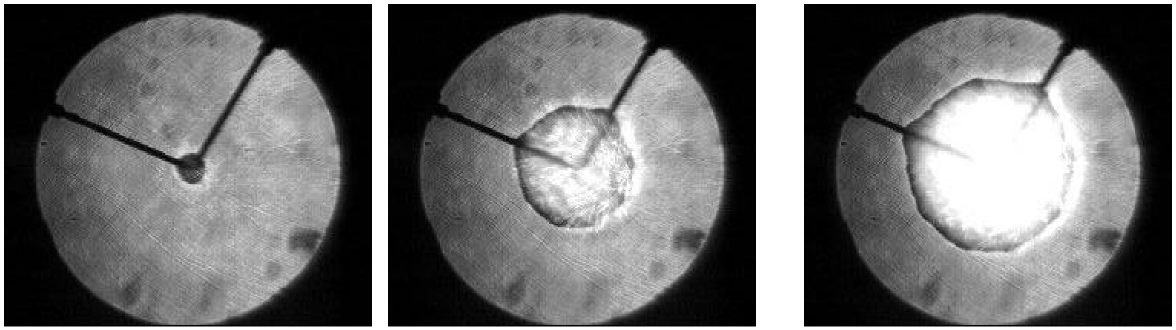


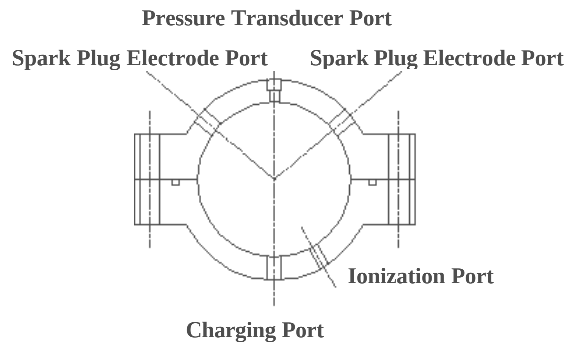




* Caterpillar Flame Speed Code

Flame Speed Measurements





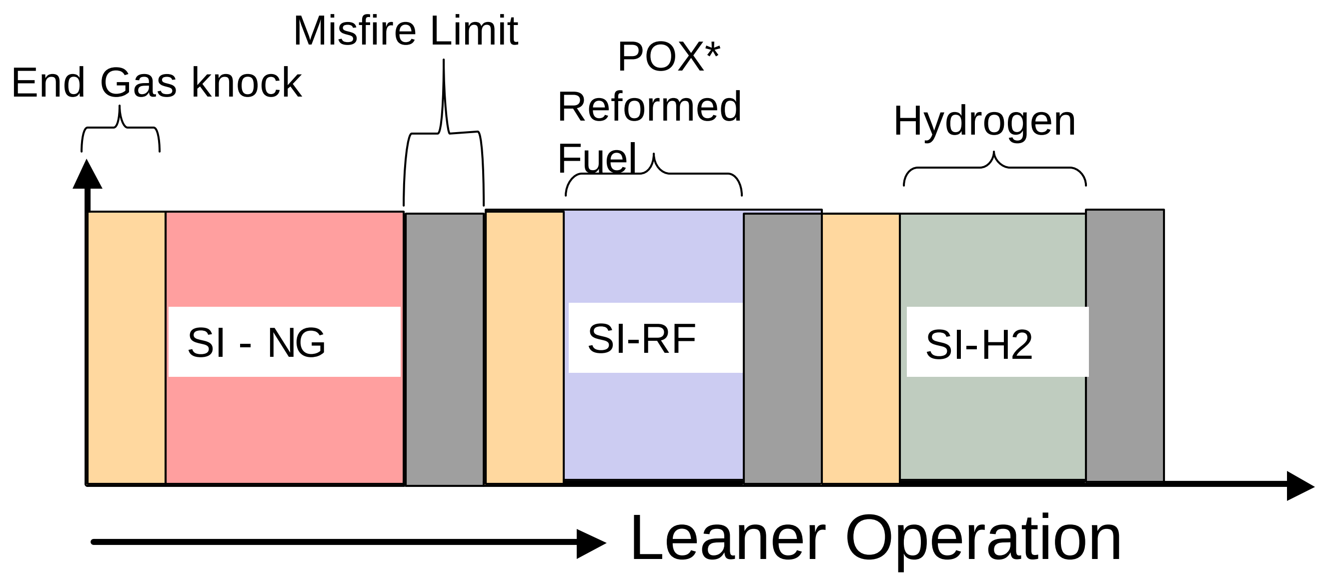
t = 3 msec, $P/P_i = 1$ t = 7 msec, $P/P_i = 1.05$ t = 9 msec, $P/P_i = 1.24$

Methane/Oxygen/Argon Mixture at equivalence ratio 1.0, P = 5 atm, T = 298K

- Experimental Facility setup with spherical and cylindrical chamber
- Challenges with flame speed measurements in gravitational field
  - Buoyancy & flame sheet cellularity -> flame stretch

Hydrogen Based Fuels

Fuel blends with great potential advantages…



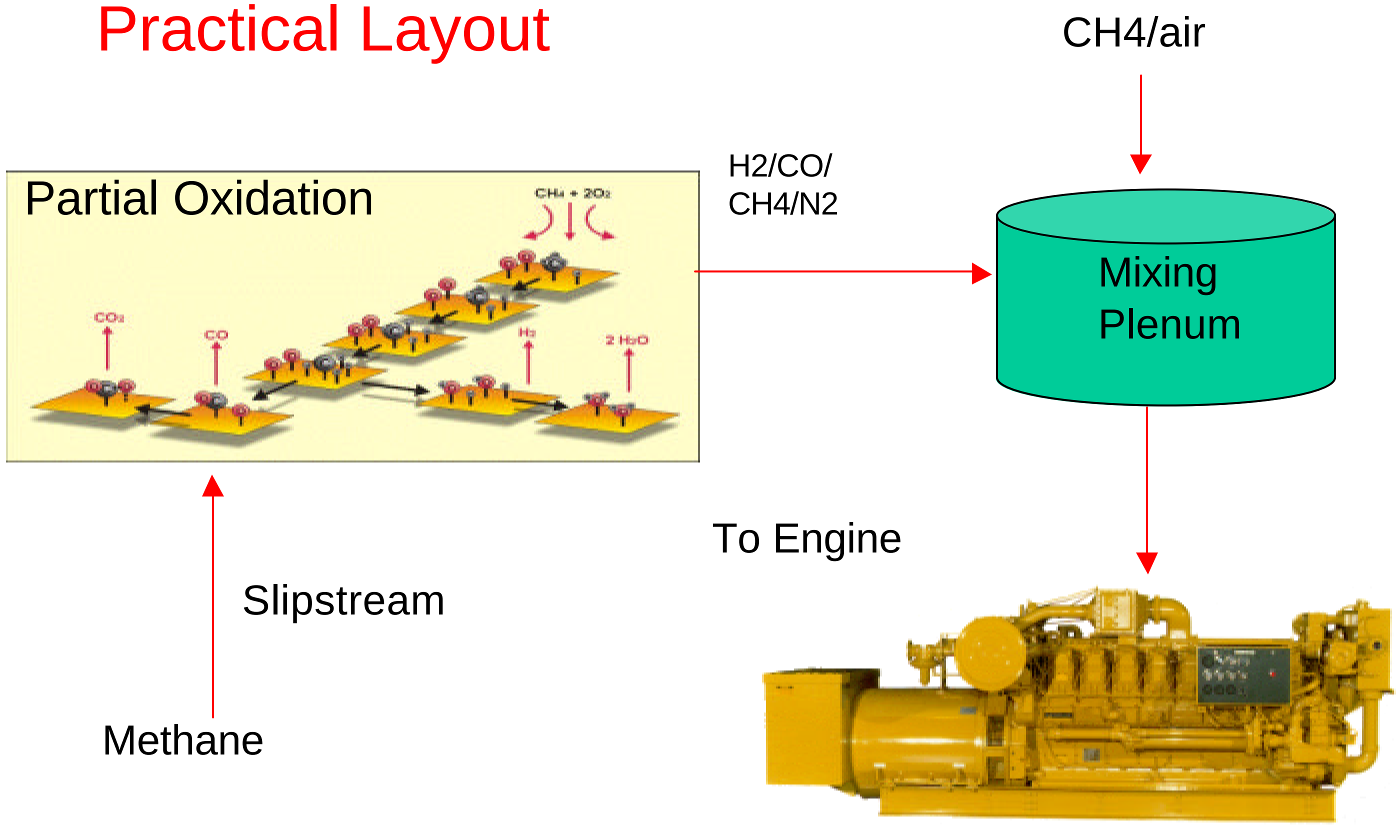
Lean Operation = Increased Efficiency and Lower Emissions

* Partial Oxidation

Reformed Fuel

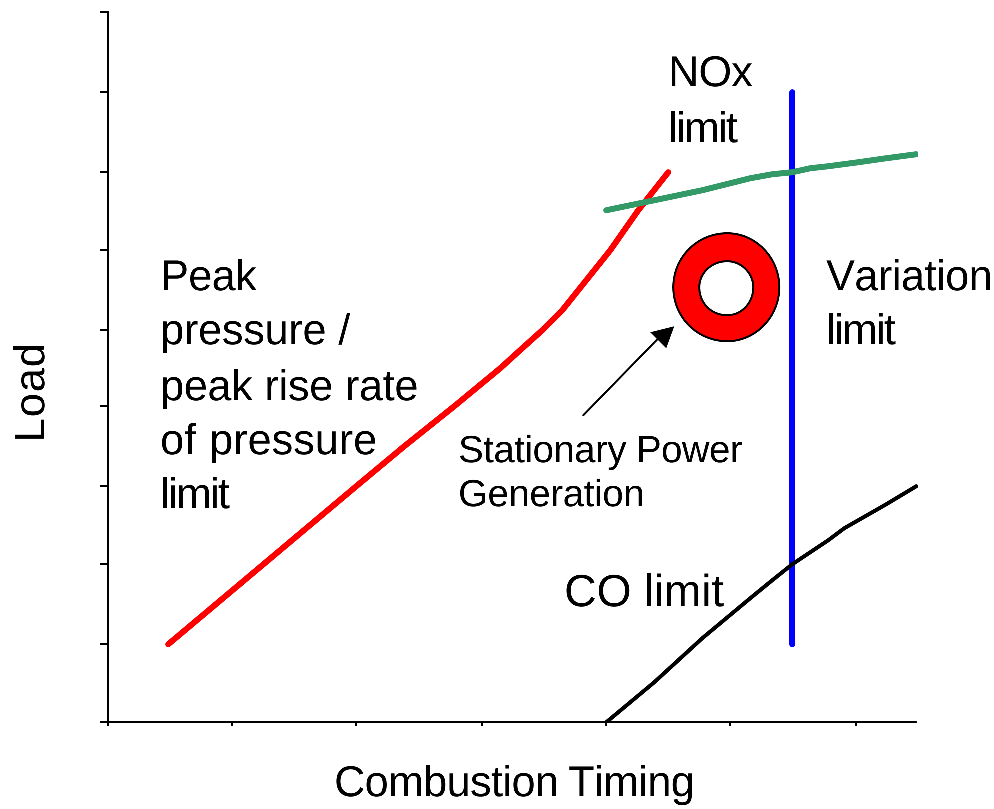
- Objective: Investigate the performance/emissions tradeoffs for reformed fuel engines

Practical Layout



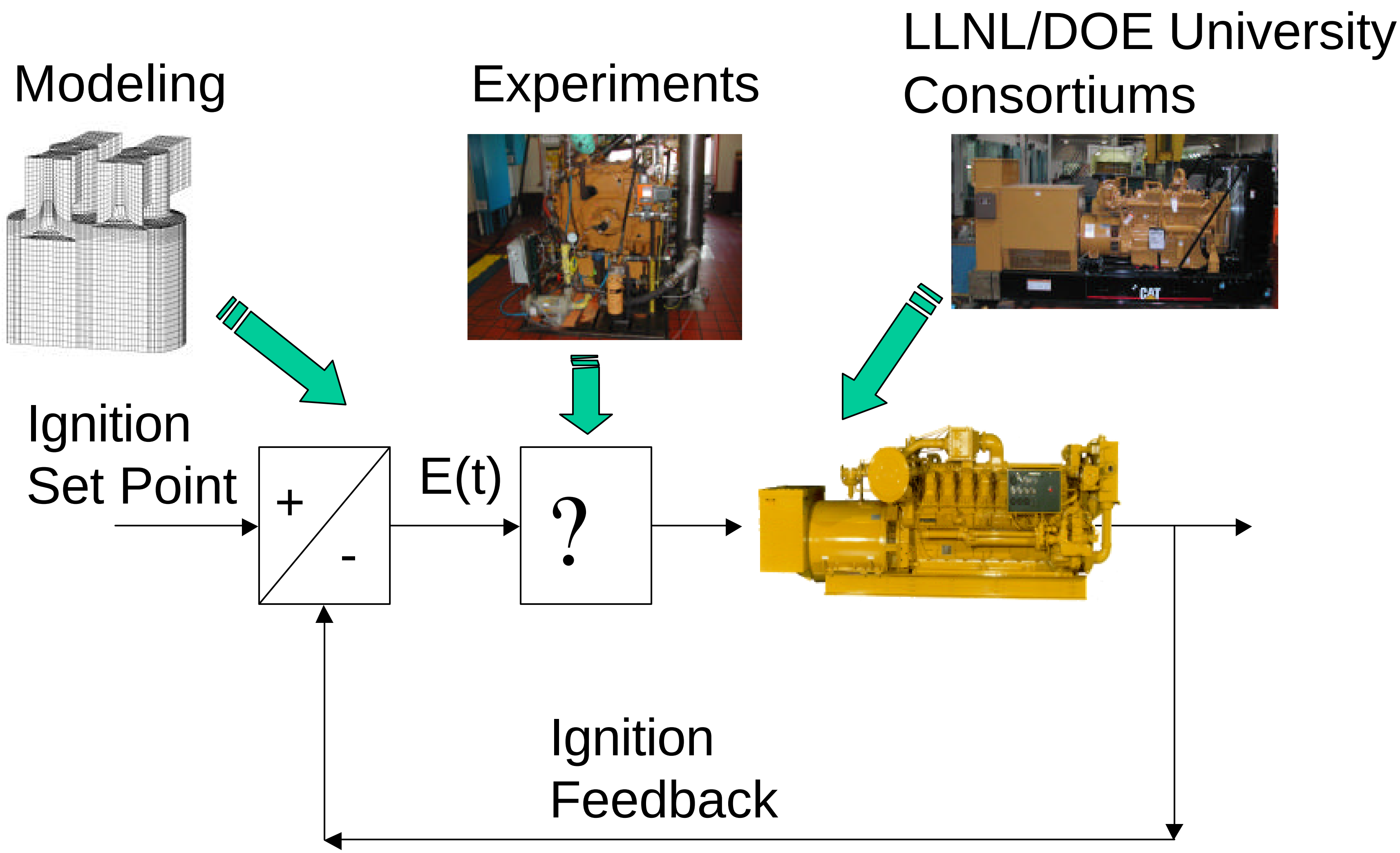
HCCI Challenges

Control of Ignition Timing



Exploring many ignition timing control possibilities

HCCI ‘Active Control’



Next Steps

- Investigate Analytically & Experimentally
  - Evolutions in the lean burn technology
  - Optimum reformed fuel arrangement
  - HCCI ‘active-control’
  - Additional phase III building blocks (i.e. heat recovery, reduced friction, etc.)
- Refine predictive tools
  - Spark-Ignition Technologies

Project Milestones – Phase I

	Main Task	Milestone
	Program Planning	Schedule High Level Plan
	Air System Concept Design	Design / Analyze Increased Pressure Ratio Turbo
	Market Study Completion	Analyze market trends and ARES participation
	Single Cyl Test Engine Design	Design basic single cylinder test engine
	Single Cyl Test Engine Build	Procure and Build single cylinder test engine
	Basic cycle simulation model	Complete initial cycle simulation model
4/02 →	**Single Cyl Test Engine Operation**	**Startup testing of the single cylinder test engine**
	SC-3* Concept Evaluation	**Fully evaluate SC-3* concepts**
	Multi-cylinder design	**Design the multi-cylinder ARES engine platform**
	Multi-cylinder build	**Build the multi-cylinder ARES engine platform**
	Reformed Fuel Concepts	**Preliminary evaluation of reformed fuel concepts**
12/03 →	Prototype Evaluation	Field test the first multi-cylinder ARES engine platform
	Pre-Production Evaluation	Complete Phase I engine pre-production validations
	Market Launch	Launch the Phase I engine for full production
	Production	Initial shipments of the Phase 1 ARES engines

* Stoichiometric – Clean Exhaust Induction - 3 Way Catalyst

Project Milestones – Phase II

	Main Task	Milestone
4/02	Program Planning	Outline a High Level Plan
	Air System Concepts	**Define air system options**
	Market Study Validation	**Validate market trends and ARES participation**
	Update Basic Cycle Model	**Complete improved cycle simulation model**
12/03	Control System Definition	Define best control system options
	Update Single Cyl Test Engine Design	Update with Phase II concepts
	Update Single Cyl Test Engine Build	Build Phase II single cylinder test engine
	Phase II Basic Research	SC-3 Testing
	HEAT™ Turbo	Introduce the HEAT™ Turbo design
	Single Cyl Test Engine Operation	Startup testing of the Phase II SCTE
	Phase II SC-3 Concept Evaluation	Evaluate SC-3 in a Phase II configuration
	Reformed Fuel Definition	Begin to evaluate reformed fuel operation in Phase II
	Other Design Integration	Incorporate other designs to be defined
	Update Multi-cylinder design	Update Phase I muiticylinder ARES engine to Phase II
	Update Multi-cylinder build / Test	Test the Phase II multicylinder ARES engine platform
	Prototype Evaluation	Field test the Phase II multicylinder ARES engine
	Pre-Production Evaluation	Complete Phase II engine pre-production validations
	Market Launch	Launch the Phase II ARES engine for full production
	Production	Initial shipments of the Phase II ARES engines

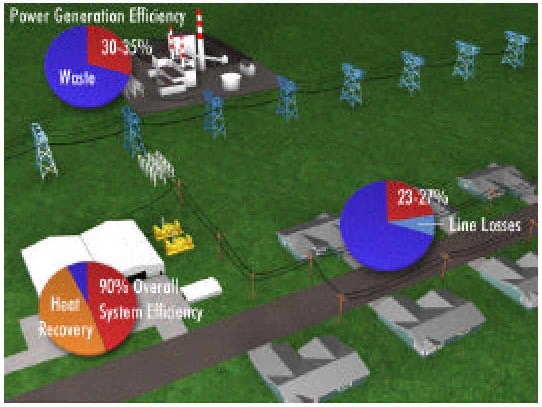
Project Milestones – Phase III

	Main Task	Milestone
4/02	Program Planning	Outline a High Level Plan
	Phase III Control Systems	**HCCI active control system development**
12/03	Phase III Basic Research	HCCI testing
	Air System Concepts	Define air system options
	Combustion System Concepts	Define combustion options
	Market Study Validation	Validate market trends and ARES participation
	Update Single Cyl Test Engine Design	Update with Phase III concepts
	Update Single Cyl Test Engine Build	Build Phase III single cylinder test engine
	Single Cyl Test Engine Operation	Startup testing of the Phase III SCTE
	Ignition System Definition	Define best ignition system options
	Other Design Integration	Incorporate other designs to be defined
	Update Multi-cylinder design	Update muiticylinder ARES engine to Phase III
	Update Multi-cylinder build / Test	Test the Phase III multicylinder ARES engine
	Prototype Evaluation	Field test the Phase III multicylinder ARES engine
	Pre-Production Evaluation	Complete Phase III engine pre-production validations
	Market Launch	Launch the Phase III ARES engine for full production
	Production	Initial shipments of the Phase III ARES engines

Program Barriers and Opportunities

Significant Risks:

- Distributed Generation / CHP Markets develop slowly
- Overall program funding limits technology pace
- Impact of Aftertreatment and Catalysis Barriers in which technical advancement remains slow.



Significant Opportunities:

- Global market opportunity expansion well beyond 10GW in 2010
- DER and CHP benefits are monitized and technology pace is spurred forward
- Lower life cycle cost alternatives clearly marketed via ARES packages
- Alternative fuels development as the market expands
- Leveraged technologies to diesel platforms, and applications beyond electric power

Program Impact on DER

-Combined Heat / Power applications are more readily adapted to ARES platforms
More financially attractive
More flexibility in electricity / heat balance

- ARES platforms can be more easily adapted to the anticipated hydrogen economy.

- Gas compression engines will see improvements in efficiency and lower emissions.

- ARES will displace 10GW of alternative DER technology:

Technology	Market	Efficiency	NOx Emissions	Hrs/yr
ARES Simple Cycle	30%	50%	0.3 lb/Mw-hr	3000
ARES CHP Cycle	70%	80%	0.3 lb/Mw-hr	8000
		- vs -		
Baseload CHP CT's	30%	60%	1.5 lb/Mw-hr	8000
Peaking CT's	50%	30%	1.5 lb/Mw-hr	2000
Diesel	20%	40%	10 lb/Mw-hr	1000

ARES Benefits NOX Savings = 30,000 Tons / year
Fuel Savings = 100 Tbtu / year

ARES Delivers !

Summary and Next Steps

Summary:

ARES
Advanced Reciprocating Engine Systems

– Program planning and initial concept development underway.

– Phase I goals in range for 2004 commercial acceptance
  – Broad customer acceptance based on improved operating costs and emissions profile.

– Phase II goals challenging, multiple paths continue under investigation.

– Phase III program continues in the research stage.

Next Steps:

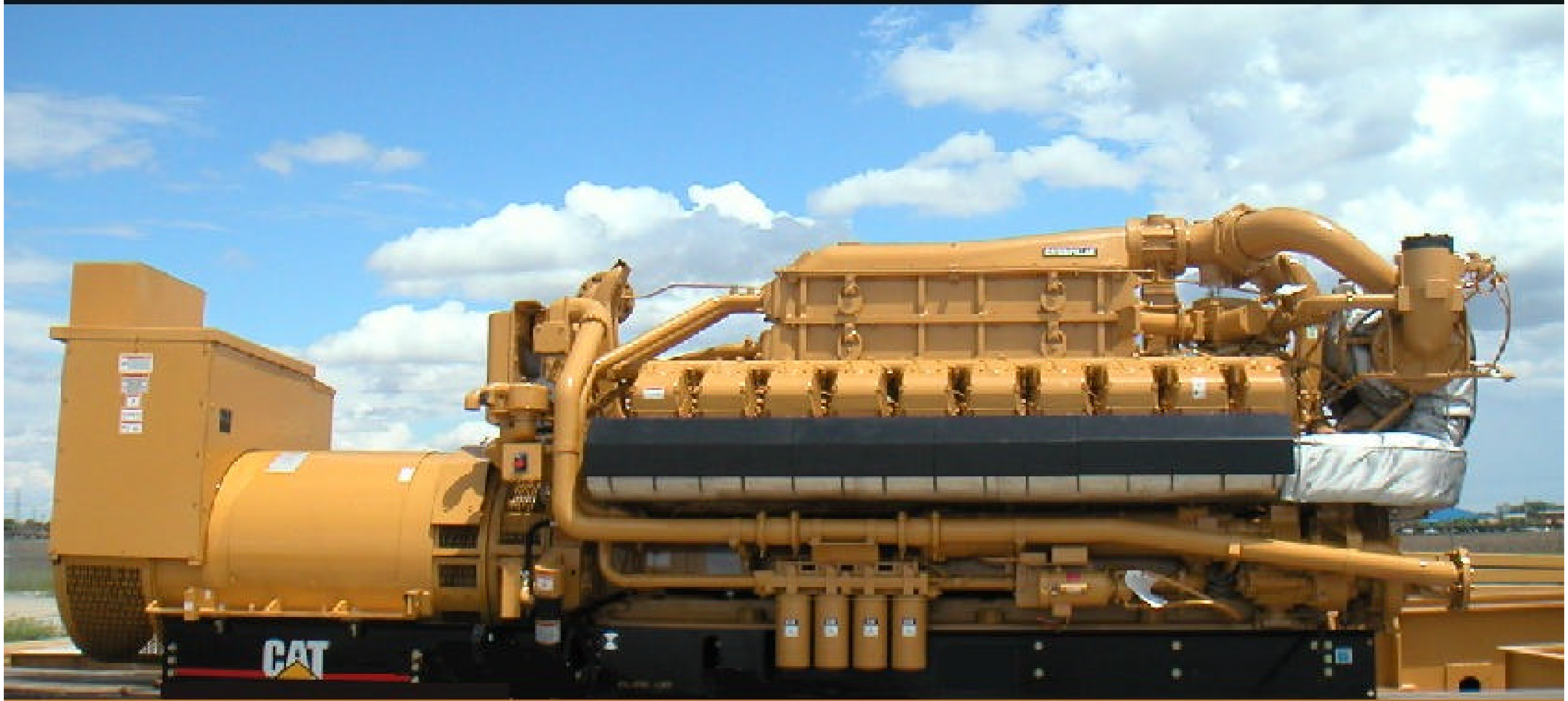
– Complete Phase I commercialization.

– Implement Phase I technology across the product line.

– Develop Phase II technical path, continue Phase III research.

– Work closely with the DOE and partners to commercialize each phase.

ARES *- The Future of Broad Based Distributed Energy Resources -*



QUESTIONS ?

ARES
Advanced Reciprocating Engine Systems